ALE-BASED FSCI COMPUTATIONS FOR SOLID ROCKET INTEIOR

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ABSTRACT

A fluid-structure interaction of solid propellant rocket interior is carried out by employing the ALE (Arbitrary Lagrangian Eulerian) description, a hybrid model of continuum motion description combining the advantages of classical Lagrangian and Eulerian description. The fluid-structure interaction process and an automatic re-meshing algorithm are included to analyze an unsteady fluid-structure interaction phenomenon with the deformation of solid grain during the simulation. The developed solver is applied for the full burning simulation of a solid propellant grain, which is a highly-coupled unsteady phenomenon between gas flow and propellant structure. Based on the integrated computed results, flow physics in the combustion chamber and the behavior of a solid propellant deformation are examined.

INTRODUCTION

During the propulsion process of solid propellant rockets, complex multi-physical phenomena are developed in the interior of the combustion chamber, due to the non-linear visco-elasticity of a propellant grain and the hot exhaustion gas formed during the burning process. Among a large number of factors influencing the rocket interior flow physics, the main factors governing the interior burning phenomena of the solid rocket are the flow of hot and high-pressure gases, the deformation of the propellant grain and combustion process. The volumetric deformation of the propellant grain caused by fluidic pressure load leads to the change of fluid domain region, and characteristics of the flow fields are accordingly varied. Flow characteristics due to the burning process and domain change trigger the change of burning rate and pressure distribution on the propellant surface. In other words, each principal element (fluid, structure, and combustion) responsible for complex physical phenomena makes a non-linear feedback cycle to influence one another. For this reason, conventional research, focusing on unveiling single disciple physics, is highly restrictive to understand the physical phenomena as a whole. The coupled simulation, by integrating fluid, structure and combustion part, is thus essential to examine the complex unsteady phenomena in a combustion chamber[1,2].

The main purpose of this paper is to develop a baseline integrated solver which can simulate the interior of solid rocket motor by coupling fluid, structure and combustion module to understand the unsteady features in the combustion chamber. In order to numerically analyze the rocket interior phenomena, the Arbitrary Lagrangian Eulerian (ALE) kinematical description, which combines the advantages of the classical Lagrangian and Eulerian ones, is adopted for the clear delineation of the dynamic fluid-structure surface. A 1-D based transient burning model and regression model are used to efficiently simulate the complicated combustion process along the propellant-fluid boundary. In addition, a robust and efficient automatic re-meshing program to handle the deformable geometry is developed to maintain a high quality mesh. Data transfer scheme between non-matching interfaces is also implemented. Each fluid-structure-regression module is combined by a staggered procedure for the time integration analysis. The integrated program is then applied to the simulation of 2-D axisymmetric solid rocket interior model including the pyrogen type igniter. Computed results show the burning process of fluid and structure domain from the initial state to the full burning state inside the combustion chamber.

NUMERICAL METHODOLGIES

ALE Kinematical Description

The ALE description is a hybrid approach combining the advantages of the Lagrangian and Eulerian formulations. In Lagrangian approach, mesh nodes are attached to continuum particles and move with them, while, in Eulerian approach, nodes of computational mesh remain fixed as continuum particles pass through them. So, it is clear that neither Lagrangian nor Eulerian approaches can properly describe the progress of solid propellant burning, because some particles are eroded due to the regression of the propellant surface. In the ALE approach, numerical simulations are firstly conducted in Eulerian manner, and deformation of computational mesh is described by Lagrangian pattern[3], which thus provides a natural numerical setting suitable for simulating the solid propellant rocket interior problem.

Fluid and Structure Analysis Module

We consider a two-dimensional axisymmetric compressible flow for the interior combustion chamber. The 3rd order TVD Runge-Kutta explicit scheme and Point Gauss-Seidel implicit scheme are used for time marching. As a spatial flux scheme, AUSMPW+, developed by Kim *et al.* to accurately capture physical discontinuities without numerical oscillation, is used[4].

Generally, the solid propellant grain exhibits visco-elastic characteristics. In this study, the mechanical response of the grain is simulated using the generalized Maxwell visco-elastic constitutive model and Mooney-Rivlin non-linear hyper-elastic model, which has been shown to be quite successful in capturing the small and large strain response of filled elastomers and developed to properly describe the energy absorbing behavior of dissipative materials, especially polymeric rubber materials[5].

Combustion Module

While combustion modeling is the crucial component for solid rocket interior simulation, actual burning rate of the contained solid propellant, which is directly related to the rocket thrust force, is determined by complex physical and chemical combustion phenomenon. For an accurate simulation of combustion process, all chemical reactions of the burning process between the grain and gases should be taken into account, which is too complicated and costly to handle. In this work, pressure and temperature of the grain surface are considered as the key components of burning process. One-dimensional transient burning model is used to efficiently simulate the burning process of an interface between fluid domain and propellant grain surface. We assume that the grain is heated by hot gas and ignited on its exposed inner surface when the grain surface temperature exceeds some specific value[1].

Spatial Data Transfer

The important requirements for the data transfer scheme are accuracy and conservation. For accuracy, the magnitude of specific error norm must be minimal, and for conservation, sum of the transferred property at both fluid and solid interface must be the same. Non-conservative schemes, such as TPS, MQ, and Cubic-spline, may ensure accuracy, but they suffer from the conservation requirement. With non-conservative schemes, we need fine meshes for both fluid and solid domain. Conservative schemes, such as node projection or quadrature projection scheme, may suffer from the accuracy requirement in case of the fluid-solid grid mismatch along the interface. This lack of accuracy or conservation can affect not only the solution along the interface but also the entire computational domain. On the other hand, the error of common refinement data transfer scheme is independent of the element mismatch along the interface. In this research, we adopted common refinement data transfer scheme for the 1-D data transfer case, to satisfy equation (1), at which conservation is more important[6].

$$v_s = v_f \text{ : Dirichlet condition for displacement,}$$
$$t_s = t_f \text{ where, } t_f = p_f n_f - \sigma_f \cdot n_f \text{ and } t_s = \sigma_s \cdot n_s \text{ : Neumann condition for stress.} \tag{1}$$

In case of 2-D data transfer, accuracy is much more important than conservation, and thus cubic spline interpolation scheme is employed to provide a reasonable accuracy with an acceptable computational cost.

Dynamic Mesh Treatment

For simulation in fluid domain, we employ unstructured mesh because it is easier to handle complex computational geometry. As stated earlier, the deformation and burnback of grain generates substantial geometrical changes in the fluid and solid domain. Therefore, FSI simulation of deformable domains requires a mesh update procedure which guarantees a high quality mesh during calculation. The mesh regeneration procedure is performed locally when a certain local geometric changes occur, and entirely when global or excessive geometric changes take place so that the local handling cannot maintain mesh quality any longer. The Rebay's point insertion technique combined the Laplacian smoothing are used as a baseline re-mesh technique for fluid domain[7]. For solid domain, we regenerate the computational 4-node mesh using Paving method during simulation.

SIMULATION RESULTS

Rocket Modeling

Figure 1 shows a typical two-dimensional axisymmetric rocket geometry designed for the simulation purpose. The blue color indicates the fluid domain, the red color shows the deformable structure domain (or the propellant grain) and the green color is the undeformable structural part composed of the rocket case, igniter and the nozzle. At the forehead of the combustion chamber, the pyrogen type igniter is modeled to eject initial hot gas which makes a grain ignite.

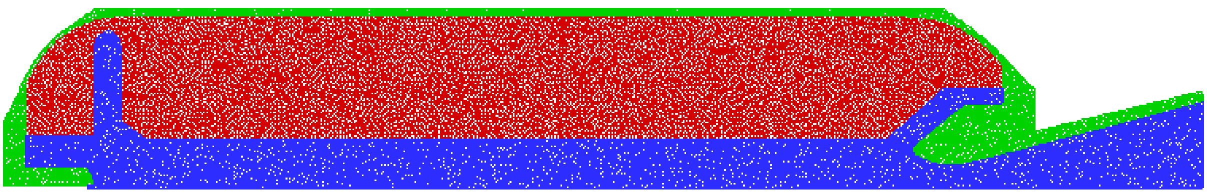

Figure 1. Rocket geometry modeling for numerical simulation

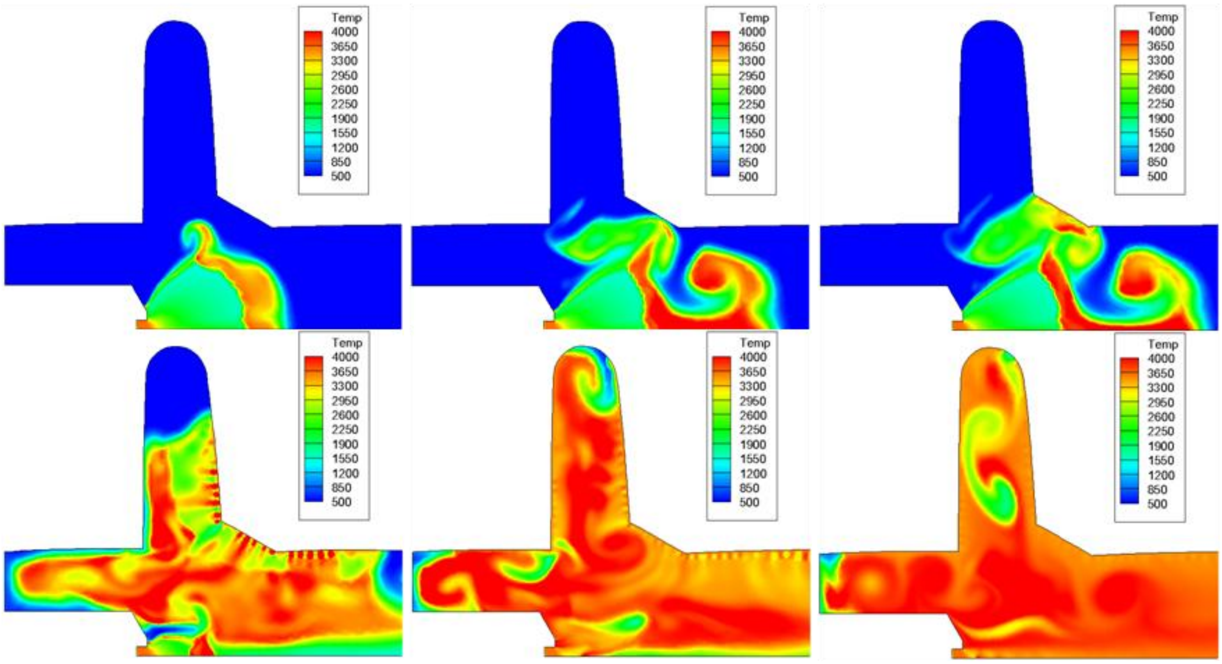

Figure 2. Ignition process of solid propellant grain by pyrogen type igniter

Numerical Results

The computational results of initial burning process near the igniter are shown in Figure 2. Flow in the combustion chamber is developed by the hot gas ejected from the igniter. The combustion gas heat the exposed grain surface especially near the trimmed slot surface, and the vicinity of the trimmed slot ignites first to send out the mass flux normal to the grain surface. Then, the flame from the vicinity of the trimmed surface heats the grain surface opposite to the slot. So, the forehead of propellant grain can be ignited almost simultaneously with the trimmed surface, though the hot gas from the igniter didn't heat the forehead grain directly. The flame propagates very fast along the exposed grain surface, while the propagation inside the slot is rather delayed since initial cold gas is congested. Finally, the chamber is filled with hot emission gas, and the whole grain surface produces mass flux.

During the combustion process, the propellant grain is burned away and deformed because of burning mechanism and a structural load from high pressure flow in the combustion chamber. Figure 3(top) indicates the geometric changing process of the solid propellant grain until most of the contained propellant is consumed for propulsion. Pressure in the combustion chamber increases instantly and reaches to the maximum point. At that time, the nozzle membrane, which is designed to contain the hot gas until the pressure loading reaches a specific value, is broken and the confined flow can be spout out through the nozzle. As a result, pressure in the combustion chamber decreases rapidly until the incoming mass flow from the burned grain and the outgoing mass flow through the nozzle are balanced. After that, internal gas pressure shows a gradual decrease, caused by the volumetric expansion of the fluid domain due to the consumption of propellant. We call this phase a steady state. In the steady, burnback velocity of the solid propellant grain is nearly constant because burnback velocity is decided by fluid pressure via the pyrolysis law. As shown in Figure 3, almost region of the combustion chamber has steady state flow variables and local changes can be observed near forehead of rocket and boots gap. Figure 3(top) also shows the difference of geometric change between convex and concave corner. the convex corner maintains initial shape but concave corner becomes locally round. Especially noticeable is the corner shape changes of the trimmed surface. The trimmed surface has two convex corners of gentle slope and, in the progress of burning, it becomes a sharp corner as shown in figure 3(top).

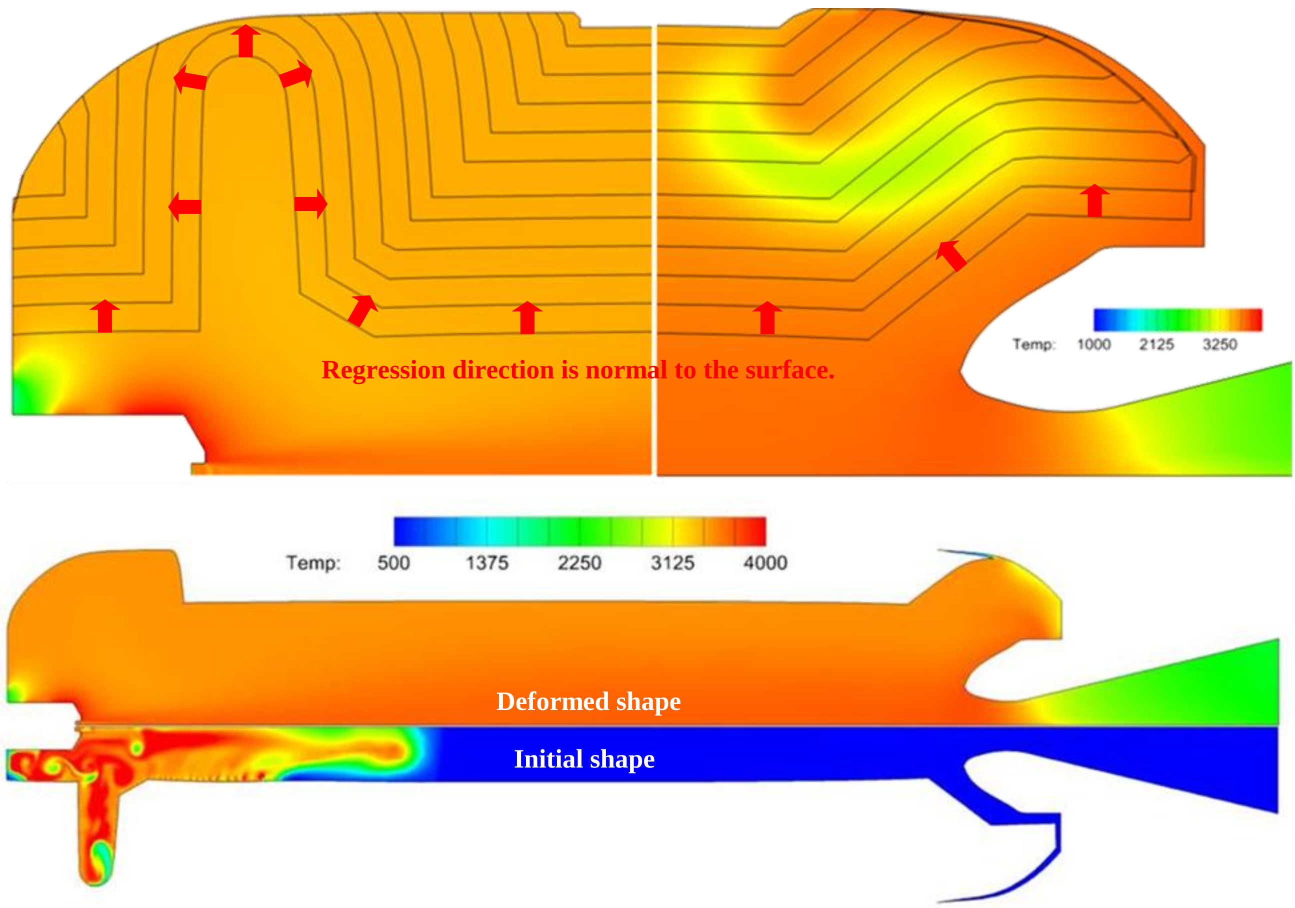

Figure 3. Computed results of the solid rocket interior integrated simulation
(top) Geometric changes during burning process of solid propellant grain
(bottom) Deformation of fluidic domain due to consumption of propellant

According to experiment, this is the normal behavior of real propellant burning so our surface regression model well captured this physical situation. Figure 3(bottom) compare the fluid domain shape after substantial burning with initial shape. A lump of initial solid propellant grain was separated into two lumps, and fore part of the separated lumps was fully burned away and only one lump of grain was remained in this figure. In this figure, we can see the steady flow feature of combustion chamber during propellant burning state compared to the highly unsteadiness of initial ignition flow.

CONCLUSIONS

An integrated fluid-structure-combustion simulation to understand the complex phenomena of the interior combustion chamber of a solid propellant rocket has presented. To accurately capture the progressive burning boundary of a propellant grain, the ALE kinematical description has been implanted into fluid/solid formulation. Two-dimensional axisymmetric compressible flow is assumed for the interior combustion chamber flow, and the mechanical response of the grain is obtained using the nonlinear hyper-elastic constitutive model. Dynamic transient burning model is used to simulate the burning process of an interface between fluid domain and propellant grain surface. To account for the deformation and burning process of a solid propellant, efficient mesh repair/regeneration algorithm and regression model are used. Some temporal and spatial coupling algorithms to integrate analysis of fluid-structure-combustion coupling problem are used. Using the developed program, we have simulated the fluid-structure-combustion coupling phenomena during the burning process in the solid rocket combustion chamber. From the simulation results, we could observe the details of initial burning and flame propagation process of the exposed propellant grain surface, and understand the structural deformation tendency of a solid propellant grain during rocket operation. Using developed FSI analysis program, we have conduct full-burning simulation of solid rocket interior. While the existing experimental test could obtain limited data of the flow fields, we could be able to obtain the history of all flow variables (pressure, temperature, velocity, and so on.) at all points of the combustion chamber and structural information (displacement, stress, and so on) of the solid propellant grain. So simulation capability of developed program can be implemented to the design or maintenance of advanced solid rocket propulsion system with a smaller outlay.

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